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Astrophysical Quark Matter

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Abstract The quark matter may have great implications in astrophysical studies, which could appear in the early Universe, in compact stars, and/or as cosmic rays. After a general review of astrophysical quark matter, the density-dominated quark matter is focused.

Key words: elementary particles — dense matter — stars: neutron — early universe

1 INTRODUCTION TO QUARK MATTER

Twenty years ago, a paper on astrophysical quark matter was published (Witten 1984), of which I will be in memory here. Anyway, let's begin with the elements of particle physics.

One of the most great achievements in the 20th century is the construction of the standard model in particle physics, which asserts that the material in the universe is made up of elementary fermions (divided into leptons and quarks) interacting though the Yang-Mills gauge bosons. The fermions have three generations (1st: $\{\nu_{\rm e}$, e; u, d$\}$, 2nd: $\{\nu_\mu$, μ; c, s$\}$, and 3rd: $\{\nu_\tau$, τ; t, b$\}$). The six flavors of quarks can be classified into light (up u, down d, and strange s) and heavy (charm c, top t, and bottom b) quarks according to their masses, and each quark is charged by one of the three colors. The elemental interactions satisfy the local gauge symmetries (sometimes to be broken spontaneously), which result in different interaction bosons: photon (electromagnetic), $W^\pm$ and Z^0 (weak), 8 types of gluons (strong), and probably graviton (gravitational). The gauge theory for electromagnetic and weak interactions is very successful, with a much high precision in calculation. Additionally, one can also apply effectively Einstein's general theory of relativity to deal with gravitational phenomena if the scale is not as small as the Plank scale ($\sim 10^{-33}$ cm or $\sim 10^{28}$ eV) although a gauge theory of gravity is still not available. However, as for the gauge theory for strong interaction, the quantum chromodynamics (QCD) is still developing, into which many particle physicists are trying to make efforts.

Nonetheless, QCD has two general properties. For strong interaction in small scale (~ 0.1 fm), i.e., in the high energy limit, the interacting particles can be treated as being *asymptotically free*; a perturbation theory of QCD (pQCD) is possible in this case. Whereas in larger scale (~ 1 fm), i.e., in the low energy limit, the interaction is very strong, which results in *color*

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confinement. The pQCD is not applicable in this scale (many non-perturbative effects appear then), and a strong interaction system can be treated as a system of hadrons in which quarks and gluons are confined. In this limit, we still have effective means to study color interaction: 1, the lattice formulation (LQCD), with the discretization of space-time and on the base of QCD, provides a non-perturbative framework to compute numerically relations between parameters of the standard model and experimental phenomena; 2, phenomenological models, which rely on experimental date available at low energy density, are advanced for superdense hadronic and/or quark matter.

These two features result in two distinct *phases* (Rho 2001) of color-interacting system, depicted in the QCD phase diagram in terms of temperature T vs. baryon chemical potential $\mu_{\rm B}$ (or baryon number density). Hadron matter phase locates at the low energy-density limit where both T *and* $\mu_{\rm B}$ are relatively low, while a new phase called *quark gluon plasma* (QGP) or *quark matter* appears in the other limit when T (*or* $\mu_{\rm B}$) is high although this new state of matter is still not found with certainty yet. It is therefore expected that there is a kind of phase transition from hadron gas to QGP (or reverse) at critical values of T and $\mu_{\rm B}$. Actually a deconfinement transition is observed in numerical simulations of LQCD for zero chemical potential $\mu_{\rm B}=0$, when $T\rightarrow T_{\rm c}\simeq(150\sim 180)$ MeV.

Physics is essentially an experimental science. Can we find quark matter in reality? Certainly we may improve substantially the knowledge about the strong interaction by studying the matter's various properties if a QGP state is identified in hand. One way is to create high energy-density fireball in laboratory through the collisions of relativistic heavy ions in accelerators. Quark matter is expected in the center of the fireball with a temperature of $T_{\rm c}$, but the QGP is hadronized soon and it is the hadronic matter to be detected in the final states. It is then a challenge to find clear signatures of QGP without ambiguousness in the terrestrial laboratory physics (lab-physics). However, it may be a *shortcut* to study astrophysical quark matter, since astrophysics offers an alternative channel for us to explore the fundamental laws in the nature.

In fact, there could be three scenarios for the existence of astrophysical quark matter (Witten 1984). 1. The temperature and density of the universe decrease in the standard model of cosmology, and it is therefore expected various of phase-transitions would occur in the early universe. One of such transitions could be $\{$QGP $\rightarrow$ hadron gas$\}$ (called quark-hadron phase transition) when cosmic temperature was $T\sim 200$ MeV. 2. Quark stars is another possibility. It is conventionally believed that pulsar-like stars, which are the residua of supernova explorations of evolved massive stars, are normal neutron stars (Lattimer & Prakash 2004) composed dominantly of neutron fluid. However, recent observations indicate that such pulsar-like stars could actually be quark stars composed of quark matter. One kind of the quark stars are those with strangeness, which can be considered to be most stable bulk quark matter (with nearly equal number of u, d, and s quarks). Such quark stars are named as strange quark stars, or simply strange stars (Xu 2004), because they have s (strange) quarks discovered in 1940s. 3. It is an alternative possibility that quark matter with baryon numbers $>10^3$ could appear in cosmic rays. Recent discovery of ultra-high energy cosmic rays may be a hint, since the energy of quark nuggets could be greater than the GZK cutoff (Madsen & Larsen 2003, Xu & Wu 2003).

There are two *different* kinds of quark matter to be investigated in lab-physics and astrophysics, which appear in two regions in the QCD phase diagram. Quark matter in lab-physics and in the early universe is temperature-dominated ($T\ll 0,\mu_{\rm B}\sim 0$), while that in quark stars or as cosmic rays is density-dominated ($T\sim 0,\mu_{\rm B}\ll 0$). (Experiments for $\{T\sim 0,\mu_{\rm B}\gg 0\}$ may be possible in the future.) Previously, Monte Carlo simulations of LQCD were only applicable for cases with $\mu_{\rm B}=0$. Only recent attempts are tried at $\mu_{\rm B}\neq 0$ (quark stars or nuggets) in LQCD. We have then to rely on phenomenological models to speculate on the properties of density-dominated quark matter by extrapolating our knowledge at nuclear matter density.

2 QUARK-HADRON TRANSITION IN THE EARLY UNIVERSE

The underlying gauge symmetry in high-temperature is much larger than that in low-T, the vacuum may then undergo various phase-transitions in case of symmetry broking spontaneously when the universe cooled as it expanded. Such transitions would result in the remnants of fase vacuum: topologically defects (0D-monopoles, 1D-cosmic strings, and 2D-domain walls), and may even induce the universe to inflate (Kolb & Turner 1990). In the early radiation-dominated universe, whose space-time is described by Robertson-Walker metric, the temperature can be approximated simply by

$$T \sim \frac{1\ \mathrm{MeV}}{\sqrt{t}}, \tag{1}$$

with the cosmic age t in unit of seconds. A electro-weak transition occurred at temperature $T_{\mathrm{ew}} \sim 100-200$ GeV when the unverse aged $t_{\mathrm{ew}} \sim 10^{-11}$ s, while a quark-hadron phase-transition (QHPT, or QCD transition) took place at temperature $T_{\mathrm{qcd}} \sim 100-200$ MeV when the cosmic age was $t_{\mathrm{qcd}} \sim 10^{-5}$ s (see a review of, e.g., Schwarz 2003).

The cosmic QHPT is very close to an equilibrium process, since the the relaxation time scale of color interaction, ~ 1 fm$/c \sim 10^{-23}$ s, is much smaller than the time interval $t_{\mathrm{qcd}} \sim 10^{-5}$ s in which the cosmic thermodynamical variables and expanding-dynamical curvature can change significantly. A first-order (or second-order, actually the order is still not certain) QCD transition may proceed through bubble nucleation. The hadronic bubbles grow, release laten energy, and could collide with others when they are larger enough (i.e., bubbles with hadron gas grew until they merge and filled up the whole universe in the end of QHPT). The horizon radius at that time is $R_{\mathrm{h}} \sim ct_{\mathrm{qcd}} \sim 10$ km. However, the typical separation between bubbles, D_{b}, could be much smaller than the horizon radius, only $D_{\mathrm{b}} \sim 10^{-6}R_{\mathrm{h}} \sim 1$ cm according to lattice QCD calculations where the bubble surface tension and laten heat are included.

The cosmic QHPT may have many astrophysical consequences which would test the physical process in turn. Big-bang nucleosynthesis (BBN) predicts the abundances of the light elements (D, ^{3}He, ^{4}He, and ^{7}Li) synthesized at cosmic age of $\sim 10^3$ s, which are observation-tested spanning *nine* orders of magnitude (number ratios: from ^{4}He/H~ 0.08 down to ^{7}Li/H $\sim 10^{-10}$). However, the initial physical conditions for BBN should be setted by cosmic QHPT. For instance, the inhomogeneities of temperature and baryon numbers during bubble nucleation may affect the abundances synthesized, which may clear the possible inconsistency of the light element abundances with the CMB measurements (Cyburt, Fields & Olive 2003). In this sense, BBN offers then a reliable probe of QHPT. As a result, this study could provide a better determination of the baryonic density in the universe.

The formation of quark nuggets could be another probable consequence. Towards the end of the QHPT, baryon-enriched quark droplets shrank, and might remain finally to play the role of dark matter (Witten 1984). Quark droplets with strangeness are conjectured to absolutely stable (Bodmer 1971, Witten 1984), and the residual quark nuggets could then probably be composed of strange quark matter with high baryon density. Can we detect such quark nuggets? Two candidates in reality: the ultra-high energy cosmic rays (UHECRs) with energy beyond the GZK cutoff and the massive compact halo objects (MACHOs) discovered through gravitational microlensing (Alcock et al. 1993). It is worth noting, that MACHOs could be probably low-mass quark stars formed by evolved stars, rather than quark nuggets born during the QHPT (Banerjee et al. 2003) if pulsar-like stars is actually quark stars. Beside, strangelets can also form through stellar process. Additionally, the relic quark-nuggets may evaporate baryons as they cool, and they can hardly exist today (Bhattacharjee et al. 1993). In conclusion, the QHPT quark nuggets could not be very necessary to understand the observations, although the existence possibility of which can not be ruled out.

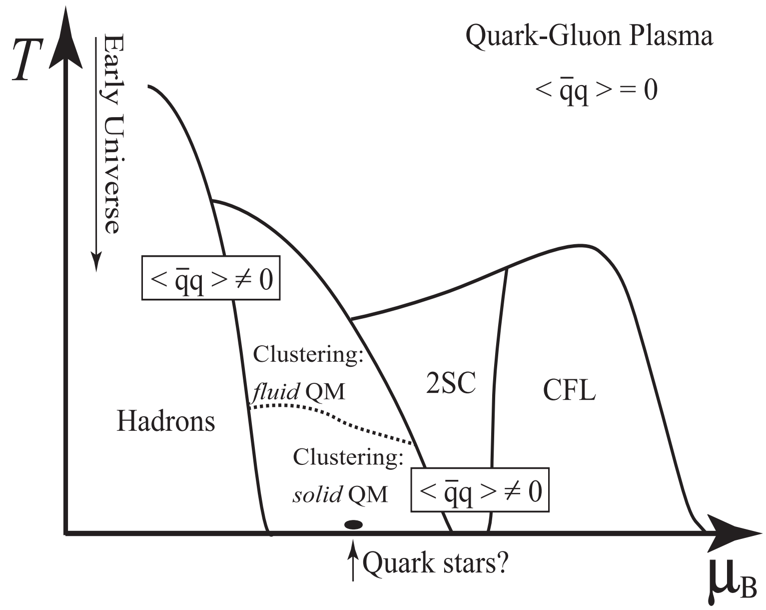

Fig. 1 Schematic illustration of QCD phase diagram.

There could be other relics of cosmic QHPT. An very interesting issue is to study the bubble collisions which may be responsible to the generation of gravitational waves (Witten 1984) as well as the large-scale magnetic walls which may lead to observable polarization correlations and density fluctuations in cosmic microwave background radiation (Kisslinger 2002). Seed magnetic fields could be produced by currents on the bubble surface (e.g., Hindmarsh & Everett 1998).

3 QUARK MATTER IN COMPACT STARS AND AS COSMIC RAYS

In different locations of the diagram (Fig. 1), besides that the interaction strength between quarks and gluons is weak or strong, the vacuum would have different features and is thus classified into two types: the perturbative-QCD (pQCD) vacuum and nonperturbative-QCD (QCD) vacuum. The coupling is weak in the former, but is strong in the later. Quark-antiquark (and gluons) condensations occur in QCD vacuum (i.e., the expected value of $\langle\bar{q}q\rangle \neq 0$), but not in pQCD vacuum. The chiral symmetry is spontaneously broken in case the vacuum is changed from pQCD to QCD vacuums, and quarks become then massive constituent ones. LQCD calculations (Kogut 1991) show that the value of $\langle\bar{q}q\rangle$ increases when the color coupling becomes strong (i.e., temperature or baryon density decrease). Therefore, we note that the quark de-confinement and the chiral symmetry restoration may *not* take place at a same time.

Considerable theoretical efforts have been made in past years to explore the QCD phase diagram. When T or $\mu_{\rm B}$ are extremely high, there should be QGP phase because of the asymptotic freedom, and vacuum is of pQCD. However, in a relatively lower energy limit, especially in the density-dominated region, the vacuum is phase-converted to QCD one but the quarks could be still deconfined. It is a hot point to investigate the possibility that real quarks may also be condensed (i.e., $\langle qq\rangle \neq 0$) simultaneously when $\langle\bar{q}q\rangle \neq 0$, the so-called color-superconducting (CSC) phases (for recent reviews, see, e.g., Ren 2004, Rischke 2004). Actually two CSC phases are currently discussed. One corresponds to Cooper pairing among the two flavors of quarks

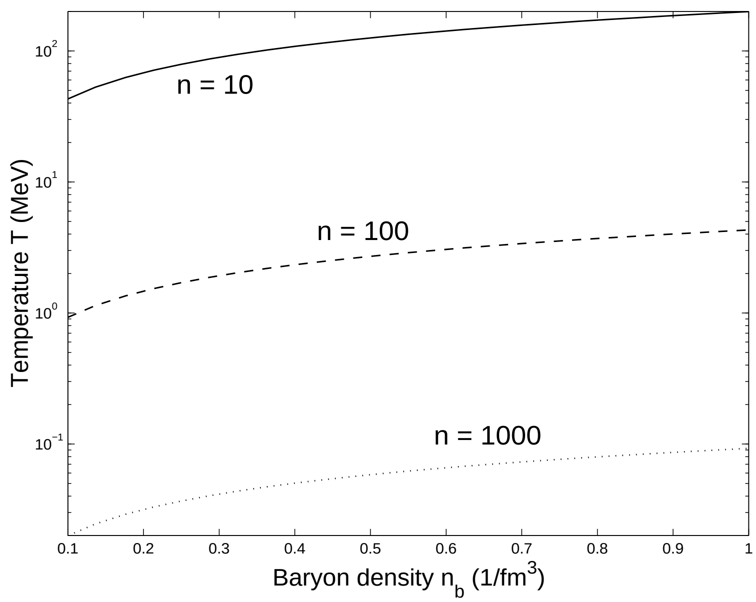

Fig. 2 The conditions that lead to quark clusters being localized in strange quark matter for different n. The condition may be satisfied above a corresponding line. The mass of an $n-$quark cluster is $300n$ MeV here. Note: the nuclear saturation density is $0.16\ \mathrm{fm}^{-3}$.

(u and d) only, the two-flavor color superconductivity (2SC) phase, in case that s quark is too massive to participate. Another one occurs at higher $\mu_{\rm B}$ in which s quarks are relatively less massive and are thus involved in Cooper pairing, the color-flavor locked (CFL) phase.

However, another possibility can not be ruled out: $\langle qq\rangle = 0$ while $\langle\bar{q}q\rangle \neq 0$. When T is not high, along the reverse direction of the $\mu_{\rm B}$ axis, the value of $\langle\bar{q}q\rangle$ increases, and color coupling between quarks and gluons becomes stronger and stronger. The much strong coupling may favor the formation of $n-$quark clusters (n: the number of quarks in a cluster) in the case (Xu 2003). Recent experimental evidence for multi-quark ($n > 3$) hadrons may increase the possibility of quark clustering. The clusters are localized[1] to become *classical* (rather than quantum) particles when the thermal de Broglie wavelength of clusters $\lambda \sim h/\sqrt{3mkT} < l \sim [3n/(4\pi f n_{\rm b})]^{1/3}$ (m: the mass of clusters, l: the mean cluster distance, $n_{\rm b}$: the baryon number density, f: quark flavor number), assuming no interaction is between the clusters. Calculation based on this inequality is shown in Fig. 2 for the case with strangeness ($f = 3$). One sees that cluster localization still exists even in very low temperature if $n \sim 10^2$. In addition, the interaction in-between, which is neglected in the calculation of Fig. 2, would also favor this localization.

In case of negligible interaction, quark cluster would become condensed when the temperature is lower than that shown in Fig. 2. However, the interaction is certainly not weak since the vacuum is of QCD ($\langle\bar{q}q\rangle \neq 0$). Now, a *competition* between condensation and solidification appears then, just like the case of laboratory low-temperature physics. Quark matter would be solidified as long as the interaction energy between neighboring clusters is much larger than that of the kinetic thermal energy. This is why *only helium*, of all the elements, shows superfluid

[1] We apply "local" to refer that "quark wavefunctions do almost not overlap". In this sense, localized clusters can still move from place to place when T is high, but could be solidified at low T.

phenomenon though other noble elements have similar weak strength of interaction due to filled crusts of electrons. The essential reason for the occurrence of CSC is that there is an attractive interaction between two quarks at the Fermi surface. But, as discussed, much strong interaction may result in the quark clustering and in a solid state of quark matter. In conclusion, a new phase with $\langle \bar{q}q \rangle \neq 0$ but $\langle qq \rangle = 0$ is suggested to be inserted in the QCD phase diagram (Fig. 2).

Nevertheless, what can we know from experiments in case of those theoretical uncertainties?

Astrophysics may *teach* us about the nature of density-dominated quark matter, since experiments (in low-energy heavy ion colliders) with low temperature but high density is only possible in the future. Two scenarios of such astrophysical quark matter: quark stars and ultra-high energy cosmic rays. Fortunately and excitedly, many astrophysical challenges could not exist any more in the solid quark star model for pulsar-like stars, e.g., the thermal X-ray spectra (Xu 2003) and the discrepancy between glitches and free-precessions (Zhou et al. 2004).

4 CONCLUSIONS

Possible astrophysical quark matter in three scenarios is explained. The nature of density-dominated quark matter could be uncovered by the study of pulsar-like stars, while it is still not sure to link astrophysical observations to cosmic QCD phase transition.

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